Stratosphere Troposphere Coupling: the influence of volcanic eruptions

Matthew Toohey[1]; Stephanie Gleixner[1]; Kirstin Krüger[1]; Claudia Timmreck[2]; Hans Graf[3]; Marco Giorgetta[2]; Alexey Karpechko[4]; Doreen Metzner[1]; Hauke Schmidt[2]; Georgiy Stenchikov[5]; Davide Zanchettin[2]

1 IFM-GEOMAR, Germany; 2 Max-Planck-Institute for Meteorology, Germany; 3 University of Cambridge, UK;
4 Finnish Meteorological Institute, Finland; 5 King Abdullah University of Science and Technology, Kingdom of Saudi Arabia

contact: mtoohey@ifm-geomar.de

1. Introduction

Stratospheric sulfate aerosols produced by major volcanic eruptions modify the radiative and dynamical properties of the troposphere and stratosphere through their reflection of solar radiation and absorption of infrared radiation. At the Earth's surface, the primary consequence of a large eruption is cooling. However, it has long been known that major tropical eruptions tend to be followed by warmer than usual winters over the Northern Hemisphere (NH) continents (Fig 1a). This volcanic "winter-warming" effect is understood to be the result of changes in atmospheric circulation patterns resulting from aerosol heating in the tropical stratosphere, and can be described as positive anomalies of the Northern Annular Mode (NAM, or equivalently the Arctic Oscillation, AO). In an analysis of post-eruption sea level pressure observations, Christiansen (2008) found that the NAM was excited in the first winter after the eruptions with statistical significance at the 95% level.

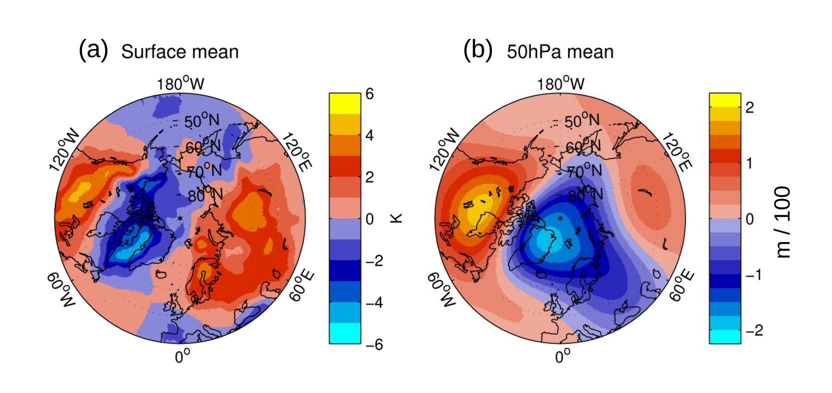

Figure 1: ERA-40 NH winter (DJF) surface temperature (a) and 50 hPa geopotential height (b) anomalies from the seasonal 9-year running mean, averaged over years 1991/92 and 1982/83, the first winters after the Pinatubo and El Chichón eruptions.

The IPCC AR4 historical simulations display only limited success in reproducing the observed tropospheric post-eruption circulation and thermal anomalies (Stenchikov et al., 2006). On the other hand, many general circulation model (GCM) experiments have successfully reproduced the apparent winter anomaly pattern. Most GCM simulations which produce realistic "winter warming" are performed with model versions specifically designed to give a better representation of the stratosphere than in typical climate models. It is thus expected that the increased use of "high-top" models in CMIP5 will lead to better agreement between modeled and observed post-eruption responses.

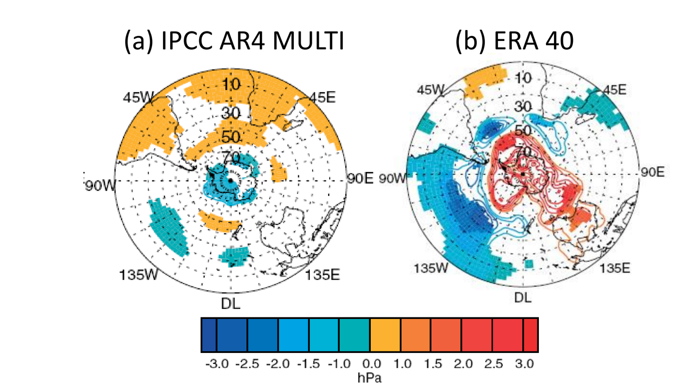

Figure 2: SH spring (OND) mean detrended SLP anomalies averaged over years 1982 and 1992 for IPCC AR4 multi-model ensemble mean (MULTI) and ERA-40, from Karpechko et al. (2010).

In terms of changes in SH circulation, Marshall (2003), Roscoe and Haigh (2007), Crooks and Gray, (2005), and Karpechko et al. (2010), all found evidence in observations and reanalysis data consistent with a negative SAM response to volcanic forcing (Fig 2b). Karpechko et al. (2010) found significant circulation changes in IPPC AR4 models in SH spring (Fig 2a) and autumn after the El Chichón and Pinatubo eruptions, although the models produced a positive SAM anomaly, opposite to the response seen in the observations.

References:
Christiansen, B. (2008), Volcanic Eruptions, Large-Scale Modes in the Northern Hemisphere, and the El Niño–Southern Oscillation, Journal of Climate, 21(5), 910.
Crooks, S. A., and L. J. Gray (2005), Characterization of the 11-Year Solar Signal Using a Multiple Regression Analysis of the ERA-40 Dataset, Journal of Climate, 18(7), 996-1015.
Karpechko, A. Y., N. P. Gillett, M. Dall'Amico, and L. J. Gray (2010), Southern Hemisphere atmospheric circulation response to the El Chichón and Pinatubo eruptions in coupled climate models, Quarterly Journal of the Royal Meteorological Society, 136(652).
Marshall, G. J. (2003), Trends in the Southern Annular Mode from Observations and Reanalyses., Journal of Climate, 16(24).
Niemeier, U., C. Timmreck, H.-F. Graf, S. Kinne, S. Rast, and S. Self (2009), Initial fate of fine ash and sulfur from large volcanic eruptions, *Atmospheric Chemistry and Physics*, *9*(22).
Roscoe, H. K., and J. D. Haigh (2007), Influences of ozone depletion, the solar cycle and the QBO on the Southern Annular Mode, Quarterly Journal of the Royal Meteorological Society, 133(628), 1855-1864.
Stenchikov, G., K. Hamilton, R. J. Stouffer, A. Robock, V. Ramaswamy, B. Santer, and H.-F. Graf (2006), Arctic Oscillation response to volcanic eruptions in the IPCC AR4 climate models, Journal of Geophysical Research, 111(D7).
Toohey, M., K. Krüger, U. Niemeier, and C. Timmreck (2011), The influence of eruption season on the global aerosol evolution and radiative impact of tropical volcanic eruptions, *Atmospheric Chemistry and Physics Discussions*, *11*(8), 22443-22481.

2. Annular mode response to tropical volcanic eruptions : coupled aerosol-GCM simulations

Here we examine how the season and magnitude of major tropical eruptions affects the annular mode response. Volcanic simulations were performed with the MAECHAM5-HAM GCM (T42/L39) including detailed aerosol microphysics (Niemeier et al. 2009). Volcanic eruptions are simulated by injecting SO_2 into the lower stratosphere (30 hPa), with model chemistry converting SO_2 to H_2SO_4 aerosols based on climatological background chemical fields. The model is run in a free running climate mode, with modern day external forcings, including climatological SSTs.

Eruption simulations were performed for a wide range of stratospheric sulfur injection magnitudes. We focus on results for eruptions of 17 Tg SO_2 injection, comparable to that of the 1991 Mt. Pinatubo eruption, and 700 Tg, a near-"super eruption". For each eruption magnitude, simulations are performed with eruptions in January, April, July and October. An ensemble of 5-year realizations are produced (n=12 and n=5 for 17 and 700 Tg SO_2 injections, respectively), initialized from different years of a 20 year control run. The influence of eruption season on surface radiation in this ensemble of runs was studied by Toohey et al. (2011).

The Northern and Southern Annular modes (NAM and SAM, respectively) are defined as the leading EOF of the hemisphere (20°-90°) monthly mean anomalies of geopotential height at 50 hPa, and sea level pressure (SLP) from the 20 year control run (Fig 1). NAM and SAM index timeseries for each volcanic simulation is calculated by regressing the geopotential height and SLP anomalies onto the EOF patterns.

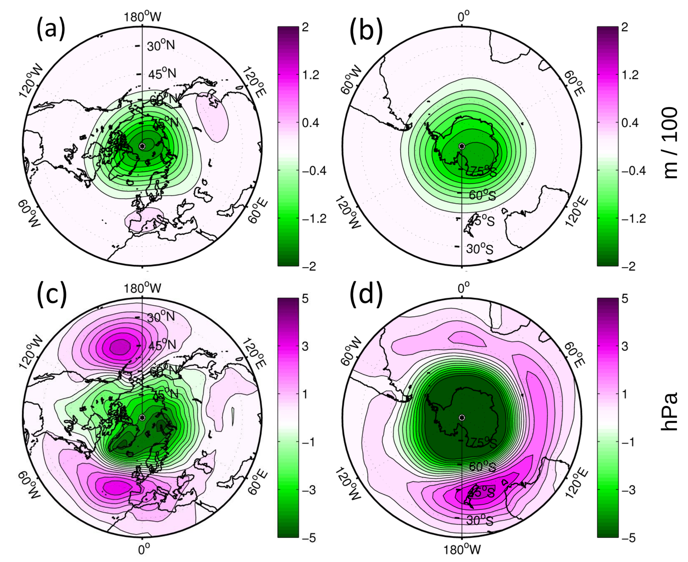

Figure 3: Leading EOF patterns from the MAECHAM5-HAM 20 year control run, for 50 hPa geopotential height in the NH (a), and SH (b), and SLP in the NH (c) and SH (d).

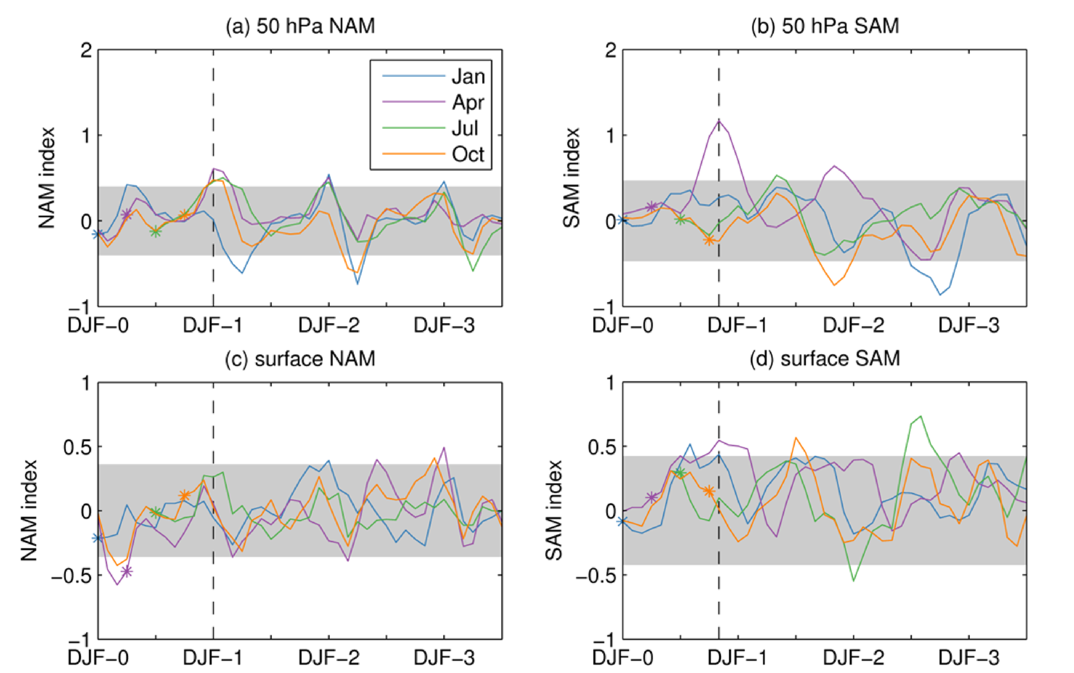

Figure 4: Ensemble mean, 3-month running mean NAM and SAM indices from MAECHAM5-HAM simulations of Pinatubo-magnitude eruptions in months given in legend. Shading denotes an approximate 95% confidence interval for the mean indices.

Pinatubo-magnitude

Post-eruption NAM and SAM at 50 hPa display noticeable sensitivity to the season of eruption (Fig 4). The first winter (DJF-1) 50 hPa NAM is positive for eruptions in Apr, Jul and Oct, but neutral (and soon negative) for January eruptions. 50 hPa OND-1 SAM is neutral for all but the Apr eruption, which shows a strong positive response.

At the surface, the ensemble mean AM responses are weak for all eruption months, although the surface SAM for Apr eruptions shows a positive persistence from spring through summer, which may be related to the positive stratospheric SAM.

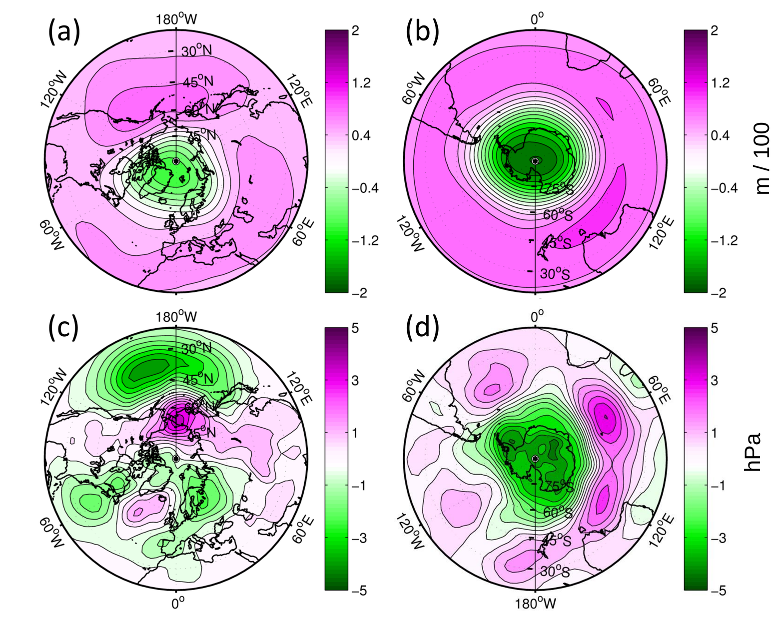

Figure 5: Ensemble mean geopotential height and SLP anomalies from the MAECHAM5-HAM runs in first NH winter (DJF-1, a and c) and first SH spring (OND-1, b and d).

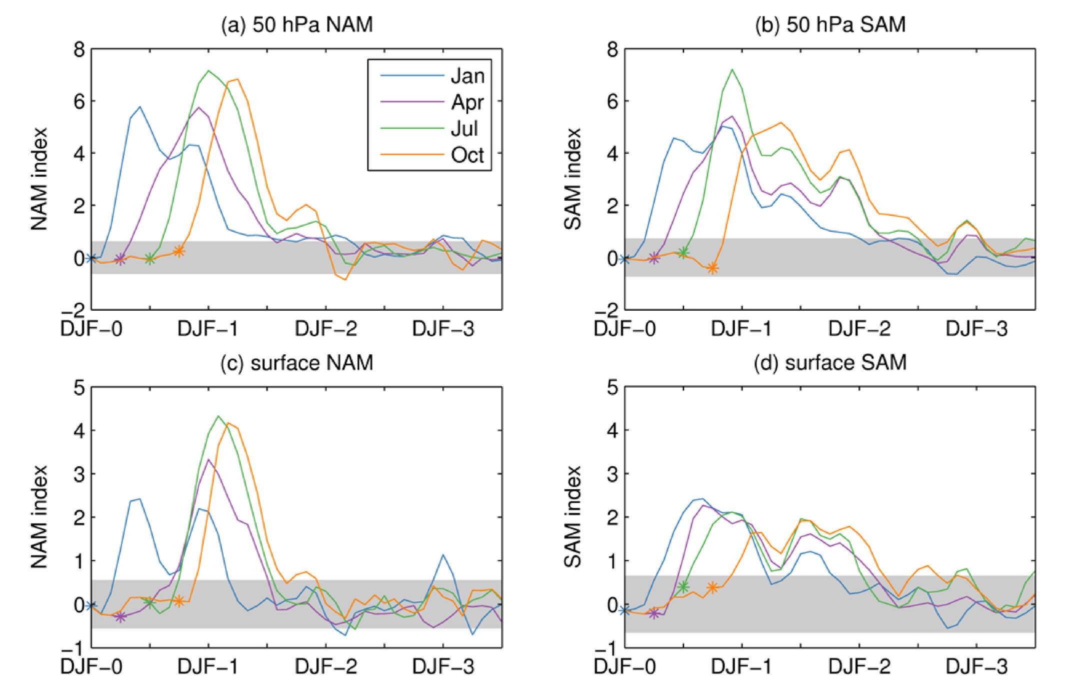

Fig 6: Ensemble mean, 3-month running mean NAM and SAM indices from MAECHAM5-HAM simulations of 700 Tg SO_2 (40xPinatubo-magnitude) eruptions in months given in legend.

Magnitudes > Pinatubo

Post-eruption NAM and SAM response is strong for a near-"super eruption" (Fig 6). NAM response, irrespective of eruption month, is strongest in DJF, while SAM response is only weakly seasonally dependent.

Annular mode response is tested for a wide range of eruption magnitudes (Fig 7). Post-eruption DJF-1 NAM and OND-1 SAM increase logarithmically with stratospheric SO_2 injection, although winter NAM shows notable variability to eruption season for eruptions >100 Tg SO_2 injection.

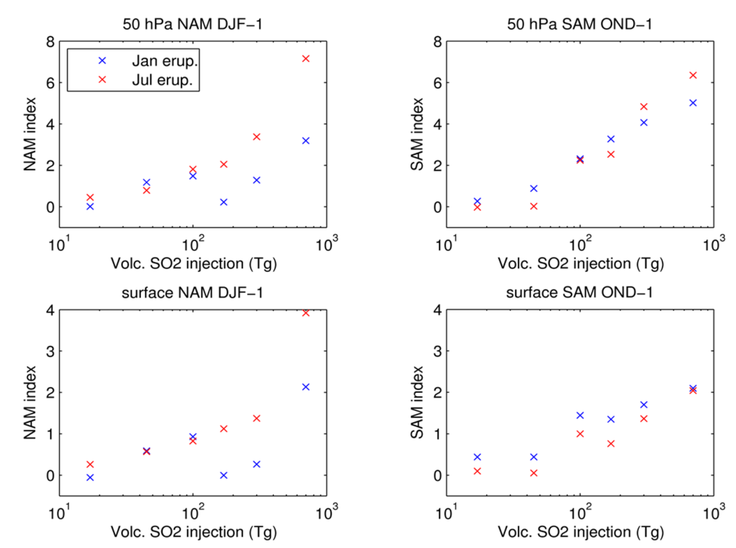

Figure 7: Ensemble mean NAM and SAM indices from MAECHAM5-HAM simulations of widely varying eruption strengths. The smallest eruption magnitude here (17 Tg SO_2 injection) is comparable to the 1991 Pinatubo eruption.

3. Annular mode response to tropical volcanic eruptions: MPI ESM CMIP5 simulations

Here we examine post volcanic anomalies from recently completed MPI ESM CMIP5 historical (1850-2005) simulations. The MPI ESM is a fully coupled earth system model, with ECHAM6 atmosphere (2°×2° resolution (T63) and 47 vertical levels up to 0.01 hPa) and MPIOM ocean (1.5°×1.5° resolution, 40 levels) components. Simulations were performed under "all forcing" conditions, including GHGs, O_3, solar, tropospheric aerosol, and volcanic aerosol.

Three ensemble members are used in the present analysis. NAM and SAM are defined as the leading EOF of the hemispheric (20°-90°) monthly mean anomalies of geopotential height at 50 hPa, and SLP from each historical run, with anomalies defined with respect to a 9-year running mean. NAM and SAM timeseries are produced from the principal component timeseries of each EOF. NAM and SAM index timeseries are averaged over the three ensemble members, and then composited around selected eruptions. We focus here on the 3 strongest eruptions in the simulations: Krakatau (August 1883, ~30 Tg SO_2), El Chichón (April 1982, ~7 Tg SO_2), and Pinatubo (June 1991, 17 Tg SO_2).

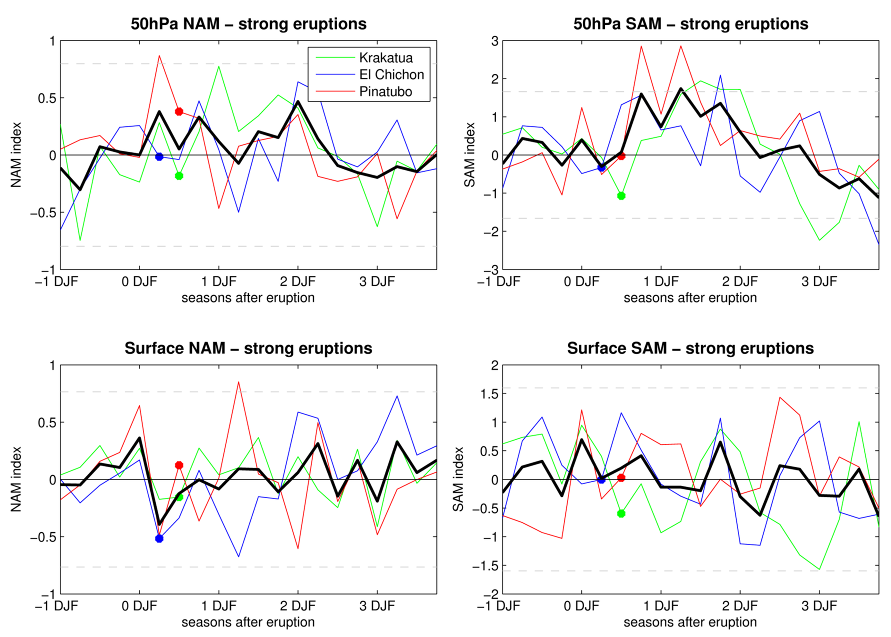

Figure 8: Ensemble mean NAM and SAM indices from ECHAM6 historical simulations around timing of Karakatau, El Chichón and Pinatubo eruptions. Black line shows composite mean for the three eruptions.

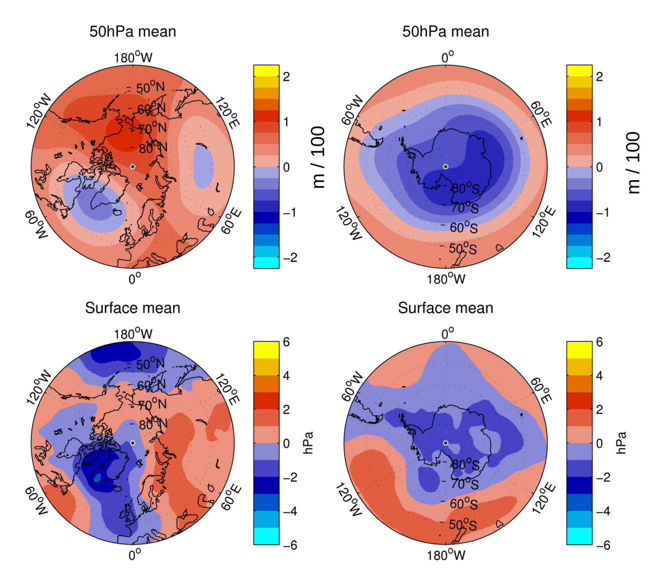

Figure 9: Ensemble mean, post-volcanic composite of geopotential height and SLP anomalies from the ECHAM6 runs in first NH winter (DJF-1, a and c) and first SH spring (SON-1, b and d).

4. Conclusions

- Season of eruption has a significant impact on the response of stratospheric annular modes in our coupled aerosol-GCM Pinatubo-magnitude eruption simulations.
  - e.g., positive SAM response in SH spring found only for April eruptions.
- Annular mode response in aerosol-GCM simulations increases logarithmically with increasing eruption magnitude: ensemble mean surface annular mode anomalies >1 require eruption of magnitude 5×Pinatubo.
- A first look at the MPI ESM CMIP5 historical runs shows very weak annular mode response to volcanic forcing
  - 50 hPa SAM shows a weak positive anomaly, consistent in sign with IPCC AR4 multi-model mean, but not reanalysis data.
- In both models, surface NAM response is less than one would expect based on observations, perhaps due to too-weak stratosphere troposphere coupling.